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A CRYOGENIC SILICON RESISTANCE BOLOMETER FOR USE AS AN INFRARED TRANSFER STANDARD DETECTOR

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ABSTRACT

We are developing an infrared bolometer to meet the needs of two detector calibration facilities at the National Institute of Standards and Technology (NIST). These facilities require transfer standard detectors with high sensitivity, accuracy, stability and dynamic range as well as a large detector area, fast time response and flat spectral response. We describe the design and testing of a bolometer to meet these requirements. This device has a dynamic range of 5 decades, a noise floor of 36 pW/$\sqrt{Hz}$, a nonlinearity of less than 1%, a spatial response nonuniformity of about 0.3% and a flat frequency response out to about 100 Hz.

1 INTRODUCTION

Absolute calibrations of infrared (IR) detectors are of increasing importance. In general, detector calibrations are made absolute by comparison to a primary standard detector, which is internally calibrated, or to a transfer standard detector that has itself been tied to some primary standard. Two specific needs currently exist at the National Institute of Standards and Technology (NIST) for absolute calibrations that require the use of transfer standard detectors. An ambient temperature facility for the calibration of IR detectors is under development. Additionally, new spectral capability is being added to the Low Background Infrared Facility (LBIR) at NIST which is used for the calibration of cryogenic detectors and sources. Both of these facilities require transfer detectors with high sensitivity, accuracy, and dynamic range as well as a large detector area, fast time response and flat spectral response. The goal of this work is the development of a transfer standard detector in the 2 to 20 µm spectral region for use in these two applications.

2 BOLOMETER DESIGN

The detector requirements of our two applications, particularly the wide dynamic range and flat spectral response, match best the characteristics of cryogenic bolometers. Since we also require a sensitive area of about 4 mm diameter, we chose a bolometer of composite design. This allows for a larger detector area while maintaining the detector speed, by using a large, thin, low heat capacity absorber bonded to a small thermal sensor. The dynamic range requirement of the bolometer is determined by two factors. The bolometer must be able to accept a large enough power to allow it to be calibrated against the NIST's primary standard radiometer which requires ~1 mW to achieve maximum accuracy. The low end of the dynamic range is determined by the two applications for this device, both of which require measurements in the nW to µW range. Since stability is important for standards work and since the response stability of bolometers can be problematic, we have made efforts, which are discussed later, to measure and reduce response variations.

Our transfer standard detector development started with a commercial bolometer [1,2] which we characterized and modified to better meet our requirements. The composite bolometer consists of a sapphire disk (0.05 mm thick by 5 mm diameter) coated with gold black to absorb incident radiation. Gold black was chosen because it has a high absorptance, while its thermal mass is extremely low. The density of gold black has been reported as low as 1/500 that of solid bulk gold (Harris and Beasley, 1992). This allows a much faster detector response than is possible with more common absorbers such as black paint or solid resistive metal films. Also, the absorptance of gold black can be greater than 90%, as opposed to the resistive metal films which may absorb up to only 50% of the incident radiation.

The temperature rise due to absorbed radiation is sensed by a silicon resistance thermometer (SRT) bonded to the back of the sapphire disk. The SRT is a doped Si chip that is commonly used in both regular (Downey et al., 1984) and composite bolometers (Dereniak and Crowe, 1984). The resistance of the

SRT depends on both the temperature and the bias current. At 4.2 K the resistance of our SRT changed from 3.6 to 1 MΩ as the DC bias current was changed from 0 to 3.5 µA (Eppeldauer et al., 1993).

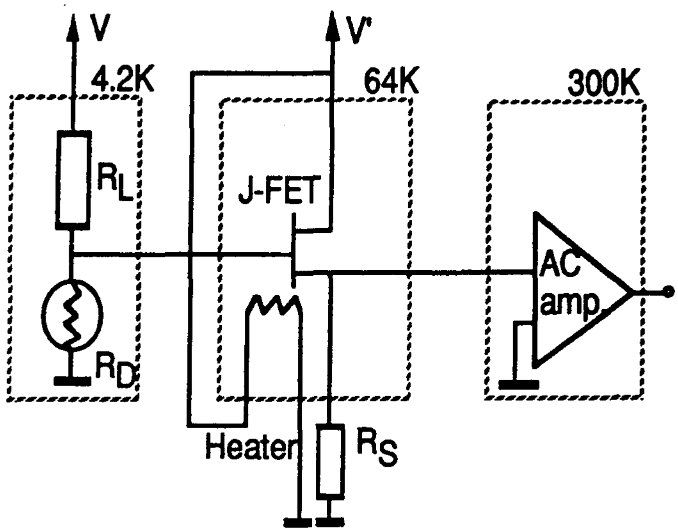

Fig. 1 SRT biasing circuit and amplifier. R_D is the SRT resistance, R_L is the current limiting resistor and R_S is the JFET source resistor. The temperatures of each section is indicated.

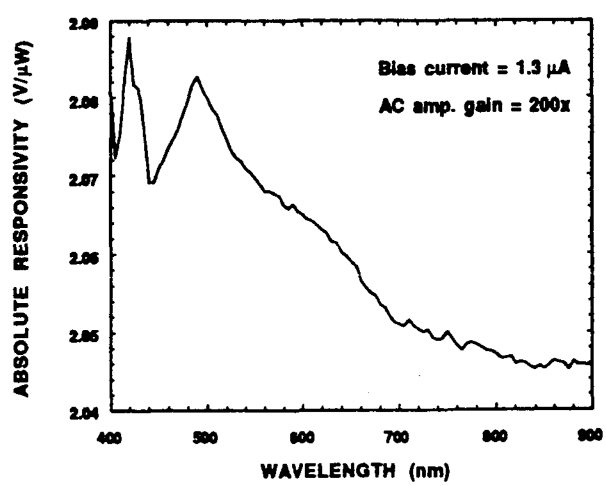

Fig. 2 Visible spectral response of the first bolometer as determined by comparison to the NIST absolute spectral response scale. The estimated 1σ uncertainty of the spectral response measurement is 0.2 %.

The SRT resistance change is measured using a unity gain Junction Field Effect Transistor (JFET) [3] followed by a selectable gain AC amplifier. The DC bias circuit of the SRT composite bolometer is shown on Fig. 1. The JFET stage is a unity gain impedance transformer between the high resistance (R_D=2.3 MΩ, R_L=10 MΩ) SRT circuit and the AC amplifier. The JFET is located in the cryogenic space near the bolometer and operates at about 64 K. The JFET's dominant noise comes from its inverse transconductance (resistor noise). Since the transconductance rises with increasing drain current, R_S should be small, but because at large drain currents the offset voltage drift, the common mode rejection, and the voltage gain stability are worse, a compromise was necessary, so R_S=10 kΩ was chosen.

3 BOLOMETER CHARACTERIZATION

The first version of our SRT composite bolometer had a flat frequency response (for chopped radiation) up to 111 Hz and a 3 dB rolloff point of 250 Hz. The responsivity was 10^4 V/W at a SRT bias current of 1.3 µA. At the nominal operating point the SRT resistance is about 2 MΩ and the electrical power dissipated in the bolometer is ~2 µW. The spectral response of the bolometer presented a problem. The spectral absorptance of the original gold black coating was found to vary a few percent in the visible and to fall to as low as 30% in the IR. Figure 2 shows the absolute peak-to-peak spectral response of the bolometer at an AC amplifier gain of 200, as calibrated against the NIST absolute spectral response scale between 400 and 900 nm (Cromer, 1991). The response variation across this range is 2%, which is significantly larger than the 1σ uncertainty of the scale realization which is 0.3% between 400 nm and 440 nm and 0.1% between 440 nm and 900 nm. Figure 3 shows Fourier Transform Infrared Spectrometer (FTIR) measurements of the total reflectance of two different gold black coatings. The reflectance of the first bolometer coating rises from less than 10% at 2 µm to greater than 70% at 14 µm. Since we intend to use this bolometer out to 20 µm we made additional specular reflectance measurements on another FTIR instrument capable of measuring up to 25 µm. Those results show that the reflectance peaks at 16.5 µm and falls toward a local minimum at 20 µm. These wide variations required us to work toward improved coatings.

The variation of response across the surface of the bolometer was checked at 900, 1200, and 1550 nm with a scan resolution of 1.1 mm. The measured variations were smaller than 0.3% over the entire 10 mm^2 aperture area.

We measured the signal and noise levels of the first bolometer with a KRS-5 window at a chop frequency of 57 Hz. The signal to noise ratio was $2x10^4$ at an incident radiant power of 7 µW. The incident power was equal to the noise floor at 20 pW with an electrical measurement bandwidth of 0.3 Hz (Eppeldauer and Hardis, 1991). We estimate the bolometer's

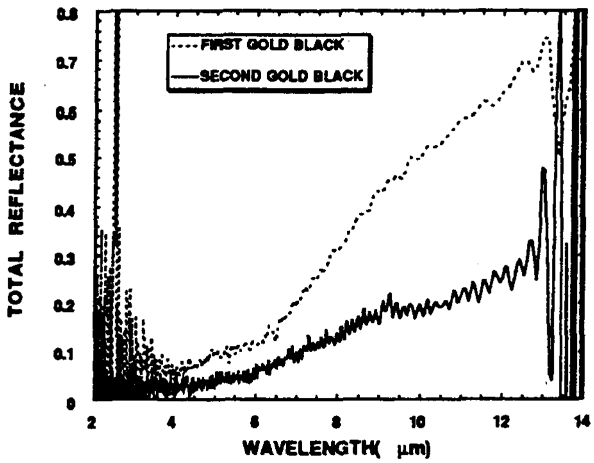

Fig. 3 Total (specular + diffuse) spectral reflectance of the first and second bolometers in the 2 to 14 μm spectral range.

minimum detectable temperature difference to be about 1 μK/√Hz from the 36 pW/√Hz noise density and the ~50 μW/K thermal conductance of the SRT leads. The bolometer dynamic range at the low power end was limited by fluctuations in the thermal background. This noise was reduced to 4 pW/√Hz when a large spherical gold mirror was placed in front of the bolometer window to image the cold bolometer absorber back on to itself (Makai and Andor, 1993). This noise is close to, but greater than, the calculated rms resistance noise of 2.2 pW/√Hz, due to the Johnson noise of R_D and R_L, scaled by the bolometer responsivity. The effective rms input noise of the AC amplifier was determined to be 1.4 pW/√Hz (using a responsivity of 10^4 V/W) which is also less than the calculated bolometer noise.

If we assume that the window passes all ambient background radiation below 100 μm, the calculated total radiant power within the f/4 field of view and incident on the bolometer is ~260 μW with fluctuations of 1.7 pW/√Hz due to shot noise (Boyd, 1983). It is not too surprising that the observed background effect is larger, as there was no attempt to control variations of the room temperature or atmospheric humidity. Note that noise observed with the bolometer looking into the room was measured only at 57 Hz with a 0.3 Hz bandwidth, so no information on the spectral variation of this noise was taken.

4 IMPROVEMENTS TO THE SILICON COMPOSITE BOLOMETER

Changes were made to improve the overall convenience of the bolometer, as well as its accuracy. There was a monotonic decrease in the bolometer responsivity after 11 hours, probably due to degradation of the dewar vacuum. Above 1.33×10^{-2} Pa (10^{-4} Torr), the poor vacuum affects the temperature of the cold plate on which the detector is mounted (Lange et al., 1983). To maintain good stability, the dewar had to be repumped every third day. During a 24 hour run, we found a period of 11 hours where the bolometer responsivity was constant to about ±0.25% (Eppeldauer et al., 1993). We suspect that the variations before and after this stable period is due to temperature variations of the cold plate and bolometer mount. The design of a new dewar with improved vacuum characteristics, temperature sensing and temperature stabilization has also been started. A carbon resistor has been added to the detector mount of the current bolometer to monitor its temperature variation.

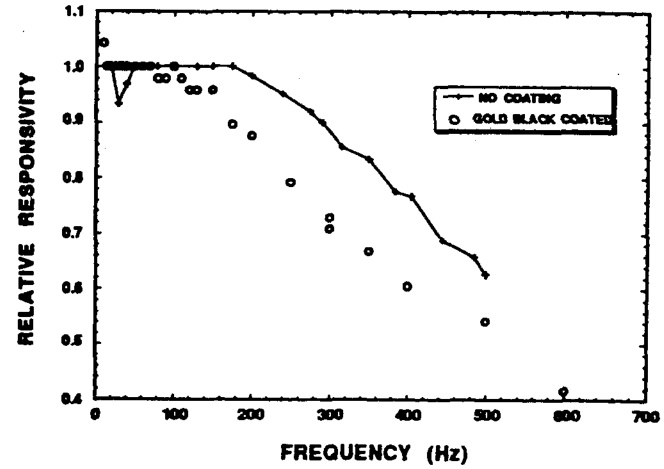

Fig. 4 Frequency response of bolometer before and after coating with gold black.

Because the first gold black coating showed high reflectivity in the IR, an improved second gold black coating was produced on a new sapphire absorber. A literature search indicated that a very low density gold black with a thickness of about 20 μm is required to achieve ~90% absorption in the 2 to 14 μm spectral region (Harris and Beasley, 1952; Harris et al., 1948). This was the goal of the second coating, although our expertise did not allow gold black coatings to be so precisely tailored. The difficulties in reproducing gold black are well noted in the literature (Advena et al., 1993; Harris, 1967). The AC frequency response of this second bolometer was measured before and after coating (see Fig. 4). The additional thermal mass of the coating shifted the 3 dB roll off point of this bolometer from 400 Hz (before coating) to 300 Hz (after coating). This is somewhat faster than the 250 Hz 3 dB point of the original bolometer. The spectral reflectivity of the second bolometer is compared to the original in Fig. 3. This coating shows significantly lower reflectivity beyond ~6 μm, although it still does not approach the design goal of 90% absorption. More coating development is needed to improve this.

The responsivity of the modified bolometer was calibrated against the NIST absolute spectral response scale. The low frequency responsivity of the bolometer in the visible was 10^4 V/W at a bias current of 1.3 μA (and before the AC amplifer), similar to the responsivity of the first bolometer.

The AC amplifier of the bolometer was also modified to allow for one decade lower gain. This allowed us to extend the point at which high power nonlinearity occurred and to determine whether the nonlinearity is due to the electronics or the sensor itself. We measured the non-linearity by measuring the transmittance of a neutral density filter at different levels of incident laser power (Eppeldauer et al., 1993). We found that the level of incident power where the non-linearity reached ~1% was the same for both the original and the modified amplifiers, although the 4% nonlinearity point in the modified unit occurs at ~3 times higher power (20 μW) (Fig. 5). The nonlinearity rises steeply beyond 1% and 4% nonlinearity points of the original and modified bolometers respectively, indicating amplifer saturation at these points. This test indicates that for incident powers below 20 μW the modified bolometer linearity is limited not by the amplifier, but by the sensor.

Nonlinearity of the bolometer can result from three effects. We assume that any variation of the signal, ($\Delta V_D = \Delta(R_D{*}I_B)$ where I_B is the bias current and R_D is the bolometer resistance) is due solely to a linear dependence of R_D on temperature. So any variation of I_B or any nonlinear dependence of R_D with temperature will result in a nonlinear response. The measured nonlinearity due to the variation of I_B as a function of incident radiation accounts for only one tenth of the observed 4% nonlinearity. This was determined by measuring the SRT resistance change of 5.4% as the incident laser power varied from 22 μW to zero. The bulk of the nonlinearity was due to the variation of the SRT resistance with bias current and nonlinear temperature dependence of the SRT.

Background radiation variations can also affect the resistance of the SRT. When the background radiation for the bolometer was blocked by a reflective aluminum plate, positioned on its window, a 1 V increase was measured across the SRT. The voltage increase was only 66 mV when the chopped 22 μW laser beam was blocked by a shutter far from the bolometer. This means a 15 times larger R_D change for the aluminum plate caused background change. To keep the bias current constant at large background changes like this, R_L should be increased. Even if the bias current is constant, the

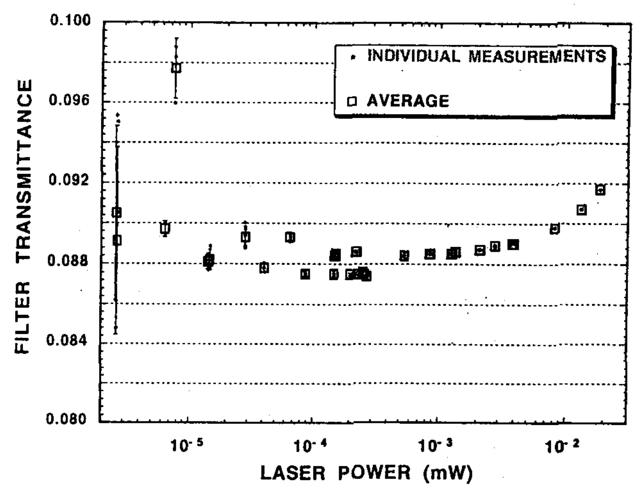

Fig. 5 Measured filter transmittance vs incident laser power with the filter removed using the second version of the bolometer. Deviation of the data from a constant value indicates nonlinearity of the bolometer. Individual measurements and the average of measurements are shown. The error bars are the standard deviations of each group of individual measurements. The apparent shift in transmittance between the two sets of points is due to repositioning the filter rather than measurement nonlinearity.

SRT resistance (and responsivity) still significantly changes for different background levels. Thus, it is important to measure the bolometer responsivity at a range of background levels. Smaller linearity and responsivity errors can be achieved if care is taken to minimize changes in the background radiation and to make R_L as large as necessary.

The dynamic range from the noise floor (with a 1 Hz bandwidth) to the 4% non-linearity point at an incident power level of 20 μW was over 5 decades. This extended high end measurement range is important for our applications as transfer standard detectors. Even with the nonlinearity, the extended range will help in tying the bolometer calibration to the primary standard High Accuracy Cryogenic Radiometer (HACR) of NIST. The signal to noise ratio of a radiometer similar to the HACR was measured to be 1.7×10^4 at an incident power of 200 μW, so we expect that at 20 μW the signal to noise ratio should be at least 1.7×10^3 (Martin et al., 1985). The HACR at NIST (Houston, 1994) has achieved similar signal to noise performance as the radiometer described by Martin et al. (1985). This signal to noise ratio for the HACR at this power level allows a scale transfer significantly better than measurement uncertainties due to the bolometer itself.

In addition to tying the bolometer calibration to the HACR, we will also use the newly acquired spectral capability of the LBIR facility mentioned earlier to independently determine the bolometer spectral response over a continuous range of IR wavelengths. The LBIR facility includes its own high sensitivity electrically calibrated absolute radiometer which has an overall absolute uncertainty of 0.12% (1σ) (Datla et al., 1992). By tying the spectral calibration of the bolometer to this absolute radiometer we will not have to depend on the accuracy of the bolometer coating spectral absorptance measurements.

5 CONCLUSION

We are developing a cryogenic transfer standard detector for use in the infrared wavelength range. This device will be used to tie IR detector calibrations to the nation's primary radiometric detector standard. Our characterization of the bolometer indicates that with the improvements already made and currently planned, we can expect to meet the requirements needed for that purpose.

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[1] References made in this paper to particular brand names or specific suppliers are for the ease of understanding by the reader and do not constitute an endorsement of products or services by the National Institute of Standards and Technology over other competitive suppliers of similar products or services, which may be equally or better suited for the purpose.

[2] Bolometer Unit #1646 in Dewar HD-3, Infrared Laboratories, Inc., 1808 E. 17th St., Tucson, AZ 85719.

[3] Siliconix family of ultra-low noise JFETs, 2N6484-E230-J230.

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